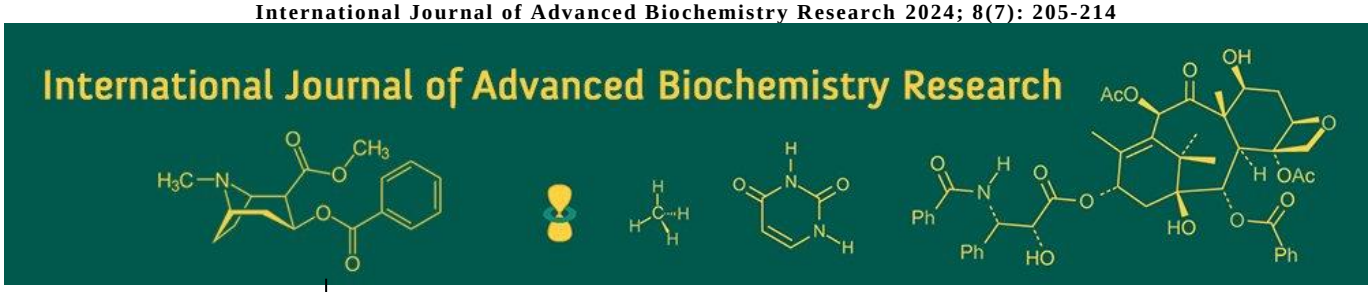

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Brassinosteroids: The promising plant growth regulators on vegetable crops: A review

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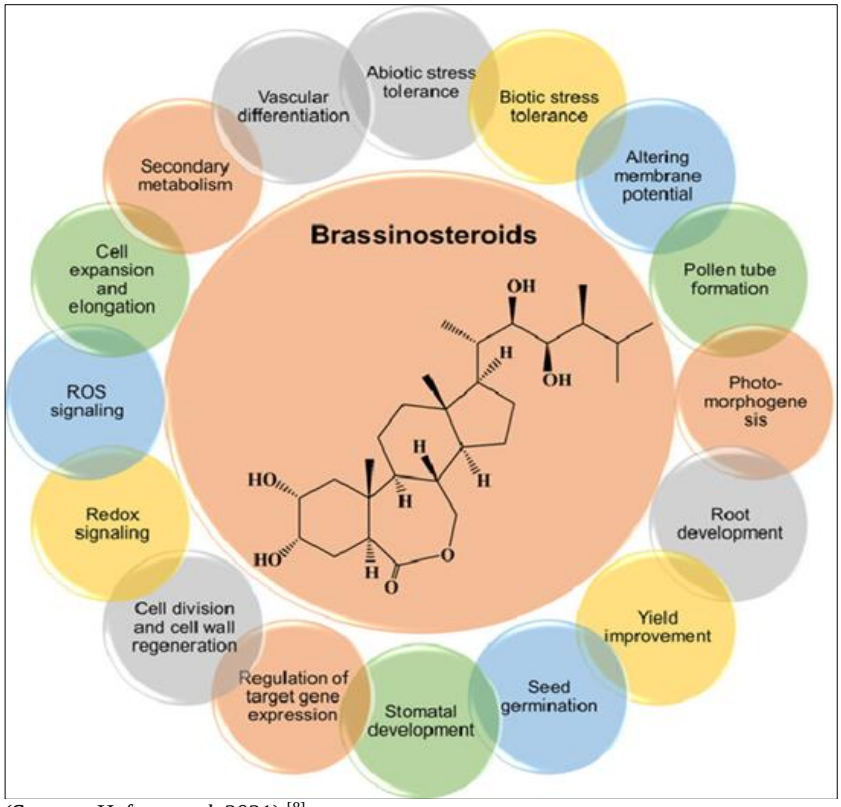
Abstract
In this research, the impact of brassinosteroids (BRs) on the production rate, quality, photosynthesis efficiency, and nutrient uptake are being assessed. A secondary qualitative analysis of the ongoing research describes how BRs contribute to plant growth, improve plants' tolerance to both abiotic and biotic stresses, and lead to agricultural sustainability. Data suggest achieving high crop yield and quality, a higher photosynthetic activity rate, and better absorption. The research points to the fact that BRs might prove effective in raising agricultural productivity and sustainability. Recommendations focus on incorporating BRs into farm crop work and increasing the research to most benefit from the BR's influence, regardless of environmental conditions or crop variety.

Keywords: Brassinosteroids, plant growth, vegetable crops

Introduction
Collectively, brassinosteroids (BRS) are a class of highly hydroxylated steroid phytohormones well-known for another reason: they play a central role in plant growth and development (Kour *et al*., 2021) [13]. BR was identified after its discovery in the late 1970s, and it acts on many growth processes, including the size and cell division, organ, and cell differentiation processes in different plants. This significantly establishes that type of agriculture, which grows crops that are resistant to various stresses. In terms of a smooth vegetable growing process that comprises a proper balance between the growth rate and the amount of produce, this type of requirement is proven to have better chances to outcompete with other requisites. Their function in this process is particularly noteworthy due to the growing evidence of the contribution of strain from the environment to agricultural output, along with climate change. Scientific research has shown that BRs can increase plant resistance to abiotic factors such as temperature extremes, soil salinity, and dryness, while, as a consideration of biotic factors, these are pests and diseases. Moreover, the plant had the role of photosynthesis, nutrient absorption, and productivity, which contributed to fast growth and materials of the best quality (Khan *et al*., 2022) [10]. This current situation of the vegetable crops' use of BRs will be reviewed by spotting their major workings, effects, and avenues of using them as sustainable agriculture management.

Research Rationale
The aim of studying brassinosteroids in vegetable crops is to enhance productivity and sustainability in light of the current world challenges such as climate change and food security. Brassinosteroids, like natural plant hormones which control growth and stress reactions, could prove to be less stressful on the plants, enabling them to become stronger and more productive. Shedding light on the above mechanisms and effects will eventually lead to recommendations that could help in achieving sustainable agriculture. Knowing that brassinosteroids might be employed commercially in such a way may result in better vegetable production that is sustainable and resilient to environmental challenges as well as profitable (Chitac, 2022) [3].



(**Source:** Hafeez *et al*. 2021) [8]

Fig 1: Molecular Mechanism Related to Brassinosteroids to Mitigate from Abiotic stresses

Research Objective

- To evaluate the efficacy of brassinosteroids in enhancing the yield and quality of various vegetable crops.
- To investigate the mechanisms through which brassinosteroids improve plant resistance to abiotic and biotic stresses.
- To assess the impact of brassinosteroids on photosynthetic efficiency and nutrient uptake in vegetable crops.
- To explore the potential of brassinosteroids as a sustainable solution in modern agricultural practices.

Research Question

1. How do brassinosteroids enhance the yield and quality of various vegetable crops, along with the underlying mechanisms that improve resistance to abiotic and biotic stresses?
2. How do brassinosteroids impact photosynthetic efficiency and nutrient uptake in vegetable crops, contributing to their potential as a sustainable solution in modern agricultural practices?

Research Gap

Although brassinosteroids have been extensively studied in terms of their effects on growth and resilience to plant stress, these steroids do have some gaps in terms of their specific impacts on photosynthetic activity and nutrition in vegetable crops. The majority of studies concentrate on model plants or staple crops, leaving a gap in the types of vegetables mentioned. Moreover, the mutual relationships between brassinosteroids and other phytohormones during nutrient uptake and assimilation remain poorly understood. The incomplete data on brassinosteroid usage creates a problem for its optimisation in different agricultural techniques. Filling these lacunae could be a valuable guide for the application of brassinosteroids, focusing on the sustainability and efficiency of vegetable production, especially under different environmental conditions.

Chapter Summary

The phrase 'Brassinosteroids' (BRs) is used to describe the sterol family, which functions by having a role in stress stabilising and growth promoting. The discovery of BRs in hydrophilic extracts of plant material in the late 1970s showed that these compounds were involved in the regulation of many processes related to the growth of plants, which also makes plants more resistant to various stresses while dealing with climate change to promote sustainable agriculture. The research will consider the effect of BRs on vegetable seeds, their quality, pest and environmental stress resistance, photosynthetic efficiency, and nutrient absorption. Furthermore, it has been established that, as to crops, especially vegetables, there is limited information concerning the function of BRs as well as how they can change other phytohormones.

Literature Review

The second chapter of the review touches on the literature about brassinosteroids (BRs) being a strength of vegetable crop yield and quality. It includes the psychological effects of BR on plant growth together with their role in stress tolerance, an outcome of looking closely into the research that demonstrates how hormones influence plant productivity. The chapter summarises what we currently know, and points out a wide variation in performance through different vegetable sorts and their responses to other environmental factors. It aims to manifest the synergy considering the application and note of honour of the principles of the BR in modern agriculture.

Overview

Impact of Brassinosteroids on Yield and Quality Enhancement in Vegetable Crops

As noted by Bhanu (2019) [2], brassinosteroids (BRs) have been established as influential and potent growth-stimulating pheromones with special importance to agricultural productivity, in particular in vegetable crops. Numerous years of research studies have proved beyond doubt that the controlled nutrition solution I have proposed can significantly improve both the yield and quality of the vegetables through diverse physiological enhancements. Research proved that these compounds promote cell growth, division, and lengthening, which are fundamentally the safeguarding processes in plants. For example, a crucial finding by Li *et al*. (2023) [14] highlighted that light pulses, in addition to significantly increasing the size and weight of tomato and cucumber fruits, were also associated with changes in the cell wall properties and increased cellular expansion.

On the other hand, there have been many reports that BRs help enhance vegetable quality attributes, which include colour, nutritive value, and desirability, enabling peasants to increase their incomes and consumers to have access to a wide-quality variety of vegetables. The paper written by Gao *et al*. (2023) [7] proved that the application of BR onto cucumbers results in higher chlorophyll content and improved resistance to yellowing, which helps cucumbers withstand ageing and improves this food for human consumption. On the other hand, investigations of green leafy vegetables, e.g., spinach and lettuce, have shown that BRs enhance the appearance and texture of foodstuffs, making them more palatable and healthier to consume.

Nevertheless, the literature proposes that different varieties of vegetable crops have diverse responses to BRs, which indicates the complexity of the interaction between BRs and plant genotypes. On the other hand, some studies may demonstrate that environmental factors like light, temperature, and soil quality can alter the effect of BRs, which can either support or counteract the hormone. This fact implies the importance of localised experiments to achieve the selected fertiliser application method optimised for particular field conditions.

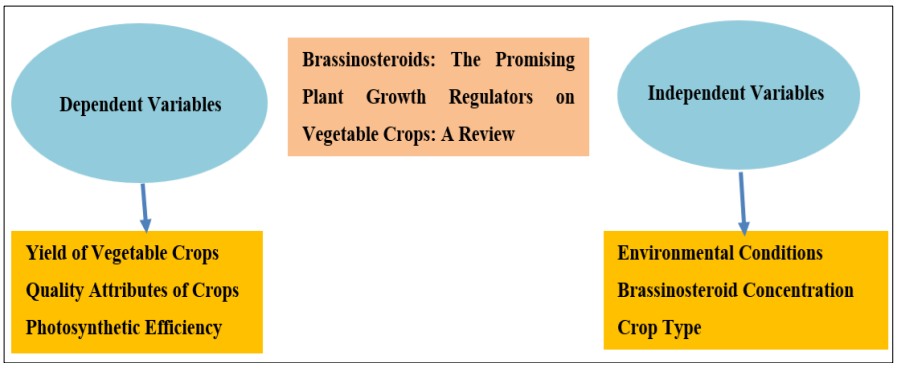
In addition, the documented yield and quality enhancement, as well as the cost-benefit analysis of using BRs for widespread agricultural enterprises, round out the picture. On the other hand, focus not only on the economic aspects of the issue but also on the whole picture of BRs' practical use in the rising output and quality of vegetables.

Brassinosteroids as Enhancers of Stress Tolerance in Vegetable Crops

As highlighted by Manghwar *et al*. (2022) [16], the particular importance of brassinosteroids in the process of plant adaptation to such diversified stresses as both abiotic and biotic is a matter of scientific policy, especially in the age of careful attitude towards climate change and its impact on cultivation. Concerning the increase in temperatures, salinity, water deficiency, and pathogens, brassinosteroids (BRs) can mitigate these environmental stress factors. A large number of research materials have shown that BRs function through biochemical pathways that regulate stress responses. The relationship between BRs and stress-related gene expression has been proven to be a key to the enhancement of anti-stress plant defence proteins. The addition of antioxidant enzymes such as superoxidase, dismutase, and peroxidase, which in turn helps to minimise oxidative stress levels as a result of environmental pressures, was highlighted by Rattan *et al*. (2020) [21]. Besides, the imbalances of the BRs involve regulating osmo protective molecules and stress hormones, which are crucial for the preservation of cellular integrity during stress.

Besides that, BRs have shown good efficacy in enhancing the power of plants against pathogens and pests. According to Yadav and his team (2022) [26], cucumber plants undergoing BR treatment demonstrated active systemic acquired resistance, which in turn helped them gain resistance against powdery mildew. This thus indicates that if the application of the BRs is embraced in pest management programmes, the use of chemical pesticides would be easily reduced and environment-friendly procedures would be adopted. Following these enhancements, the literature is debatable about whether epigenetic reprogramming (BRs) directly mediates the response to stress or the long-term effect on plant health and the ecosystem community. Undoubtedly, such studies are necessary to reveal the functioning mechanisms of these compounds and to establish optimal dosages and application methods that provide tolerance to stress conditions but do not endanger the environment or human health. In addition, this type of research is critical in the development of varieties of vegetables that can tolerate harsh situations resulting from climate change, thereby ensuring food security and agricultural sustainability.

Theoretical Framework

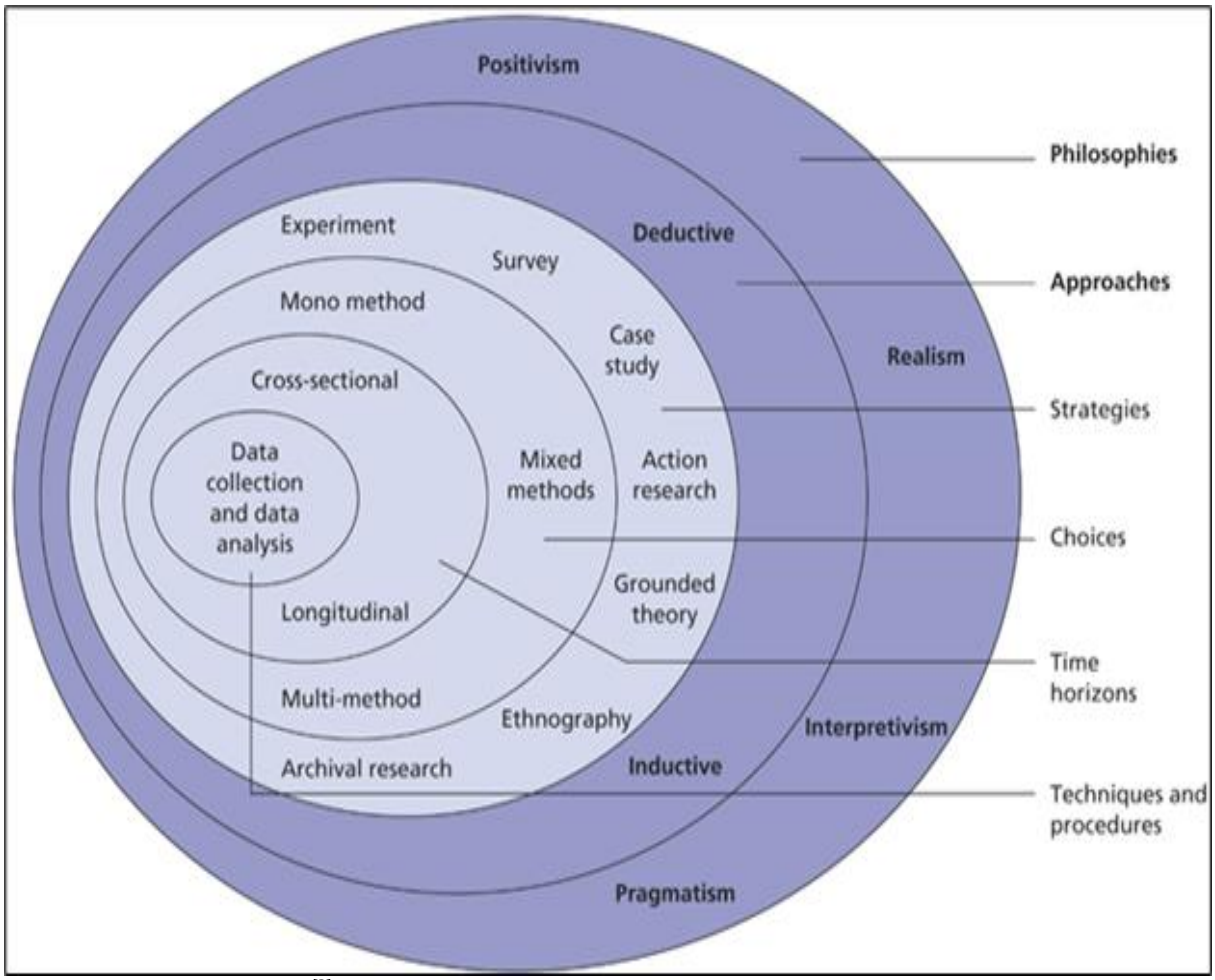


Literature Gap

Although the literature on brassinosteroids (BRs) is extensive, considerable knowledge gaps persist, mostly focusing on the specific activity of photosynthesis and nutrient uptake in diverse crops. The majority of studies revolve around model plants or staple crops, often overlooking the knowledge potential of less common vegetables. Furthermore, interactions between BRs and

other phytohormones during nutrient uptake have not been studied well enough, which affects the adoption of BR applications in varied farming settings. Filling these gaps is the key to a customized usage of BR which emphasizes sustainability and efficiency in vegetable production under different environmental conditions.

Chapter 3: Methodology



(**Source:** Saunders *et al*., 2007) [2]

Fig 1: Research Onion Model

Research Philosophy

The research is interpretive in its methods, seeking to reveal the true context and the very essence of brassinosteroid resistance in vegetables using the resulting research (Kirongo & Odoyo, 2020) [11]. It makes use of a qualitative secondary research approach, which relies on the critical evaluation and synthesis of published data regarding host plants and attempts to explain how brassinosteroids help in growth promotion, stress tolerance, and productivity. This philosophical approach also allows claiming the subjective interpretation of the secondary data for taking a holistic interpretation of the multi-faceted part of brassinosteroids in agriculture and determining the weak aspects to investigate further.

Research Approach

The current research combines deductive and qualitative secondary methods. This review aims to scrutinise the current literature and data on brassinosteroids and their effect on plant growth and stress tolerance on vegetable crops for the validation of existing theoretical frameworks and hypotheses regarding plant growth, productivity, and stress tolerance. This approach pools in the data of all the preceding studies without having to conduct new data collection, which leads to an in-depth understanding of brassinosteroid mechanisms and impacts The central theme of the article involving qualitative data interpretation is to determine the implications and possible uses of these plant hormones in environmentally friendly agriculture (Opie, 2019) [19].

Research Strategy

The research strategy of this research consists of a focus on a thorough literature review as one of the principal segments of the secondary qualitative method (Snyder, 2019) [24]. This is entirely about digging for and critically sizing up scientific papers, reviews, and case studies on the effect of brassinosteroids on vegetable crops. Through selective article picking that defines the physiological consequences, mechanisms of action, and agronomic benefits of brassinosteroids, the study will bring together all the already known knowledge and identify areas that require additional research. This review will therefore serve as a solid base around which both the theoretical and practical aspects of sustainability and productivity improvements in agriculture will be built (Olivia, 2019).

Research Choices

The research method of the study is a qualitative mono-method that involves secondary data analysis. Such a choice will include a thorough analysis of existing studies that are reviewed to carry out a synthesis without data retrieval. This method would enable the granular scrutiny of the conceptual and theoretical ideas that form the basis of brassinosteroid research in vegetable crops.

Time Horizon

In the research, a cross-sectional time frame is employed in reviewing data collected from available studies at a particular point in time. This provides a snapshot of current information on brassinosteroids in vegetable crops, which also offers immediate insights instead of the requirement of longitudinal tracking (Zolfagharian *et al*. 2019) [28].

Data Collection

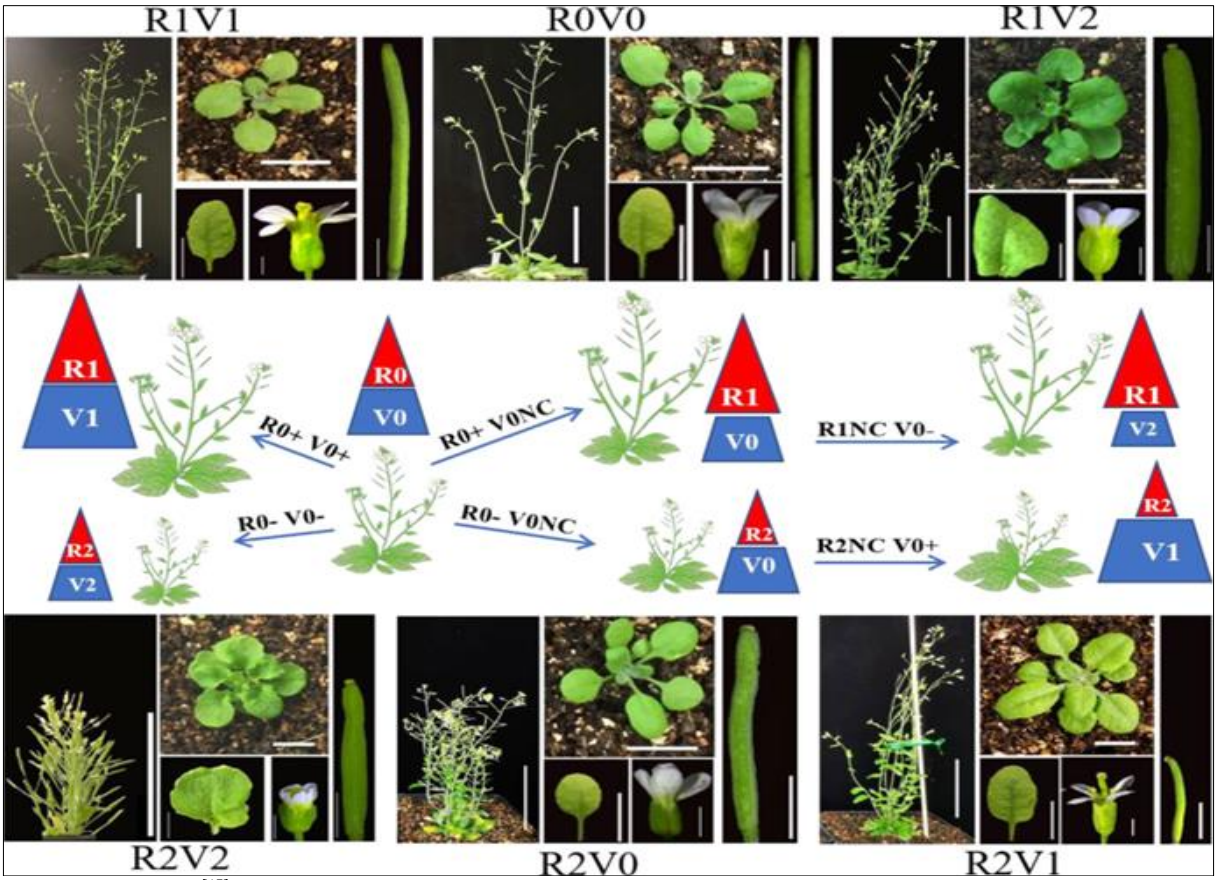
This research uses a secondary qualitative method that involves the collection of big data in the form of information from existing research such as articles, journals, and databases regarding brassinosteroids. The sources include scientific documentation like review papers that outline the physiological effects, mechanisms, and horticultural application of brassinosteroids in vegetable crops. Data is meticulously extracted to include the main results, methodology, and conclusion of the previous studies, and this is considered a robust evidence base, which is the accumulation of knowledge (Sileyew, 2019) [23]. By such a method, one can obtain an integrated analysis of different studies to conclude certain generalisations, grasping all the key issues that are not otherwise possible to only primary and secondary data collection.

Data Analysis

This chapter delves into the analysis of data gathered from secondary sources to address the two core research questions of this study: the effects of brassinosteroids on crops, i.e., increased yields and quality, improved photosynthesis, and nutrient uptake. This thesis seeks to examine the function of brassinosteroids on agricultural sustainability and productivity by using different research findings. The effects are then split into segments that deal with how brassinosteroids affect crop quantity and quality and boost photosynthetic and nutritional uptake, classifying it as a green agronomic practice.

Analysis of Research Question 1: Enhancement of Yield and Quality

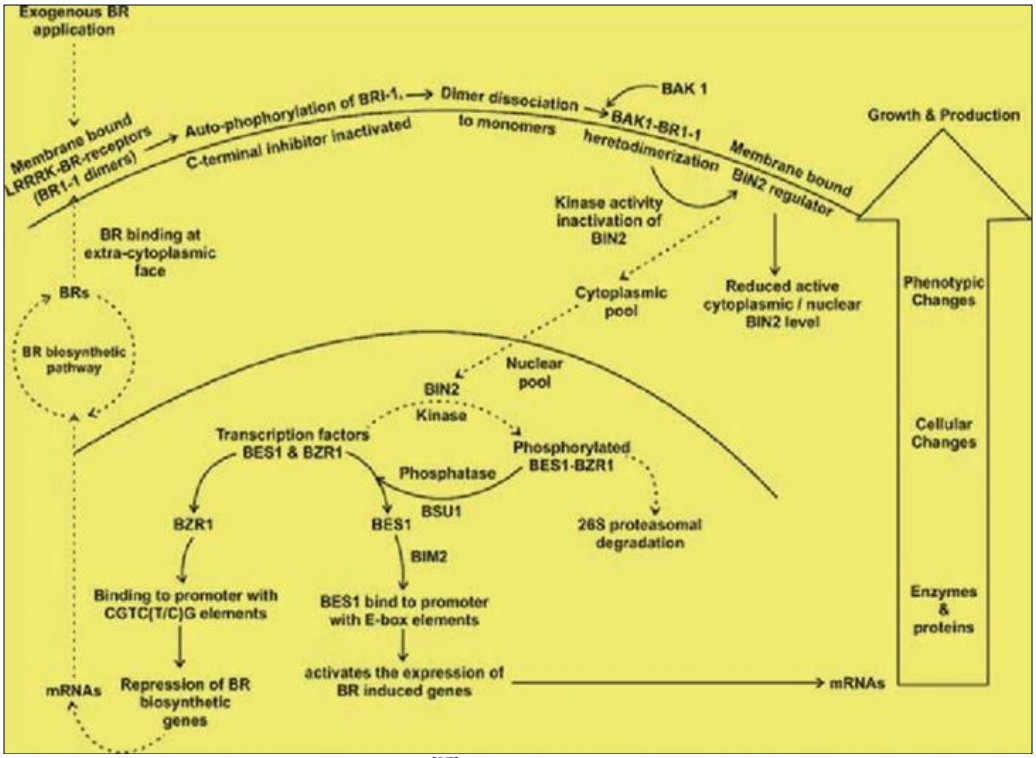
BRs are very important and have impacts on vegetable production and quality. The review presents that BRs direct plant development by activating cell-level mechanisms such as cell elongation, division, and differentiation (Lin, 2020) [15]. The hormones are known to trigger the genes and activate the pathways, which further leads to protein synthesis, which is very important for structural and functional roles. This in turn causes the growth of the plant itself (Figueroa-Macías *et al*. 2021) [5]. Additionally, as issues diminish, BRs create larger and more abundant fruits and vegetables. Most likely because the small organisms speed up the photosynthesis rate, which then provides energy, leading to an increase in water uptake and nutrient score for the plants to thrive, which is necessary under the changeable soil conditions. Moreover, BRs are increased at the cell cycle regulation gene expression level; demonstrating plants are more proliferous.



(**Source:** Lin, 2020) [15]

Fig 2: Impact of Brassinosteroids on Yield and Quality Enhancement in Vegetable Crops

In the context of quality, BRs play a crucial role in the colour, texture, and nutritional content of the crops (Raju, 2021) [20]. For example, the increased photosynthetic activity results in increased levels of essential nutrients and antioxidants in crops. They further determine the formation of secondary metabolites, which are responsible for the colour and flavour of vegetables, and thus make them more palatable and nutritious.

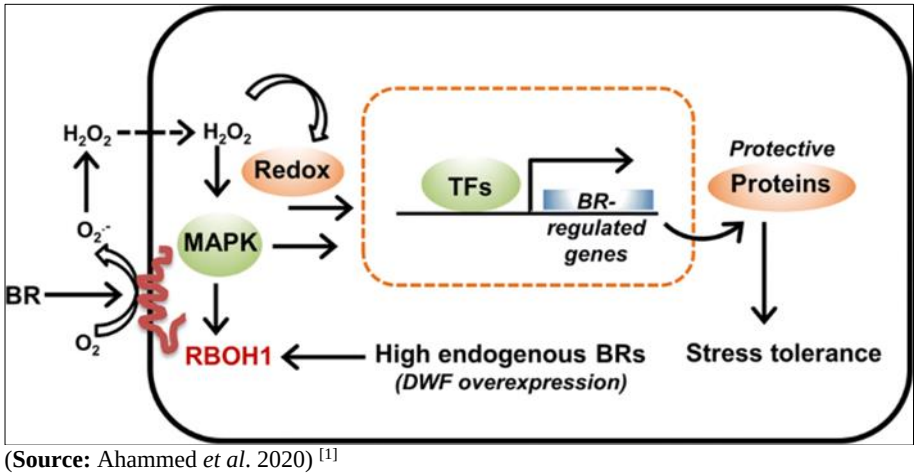


(**Source:** Yusuf, Khan & Fariduddin, 2017) [27]

Fig 3: Mechanism of Brassinosteroids Formation

Analysis of Research Question 2: Impact on Photosynthetic Efficiency and Nutrient Uptake

Brassinosteroids that help to enhance photosynthetic activity and nutrient intake are the prime factors that prompt their use in sustaining agriculture. Plants with the capability of BRS are more active and high in photosynthetic enzymes (Ahammed *et al*. 2020) [1]. Accordingly, the conversion happens easier since this chemical energy is the source of life, which is used by plants to determine their growth and productivity. In the process, it appears that BRs change the root structure and functions, and so, they enhance the ability of the plants to take up water and minerals from the soil. It is very important in situations under stress when elements are hard to find. The data suggest that BRs cause the gene expression of specific enzymes and transporters that enable plants to take these essential elements from the soil, i.e. nitrogen, phosphorus, and potassium.



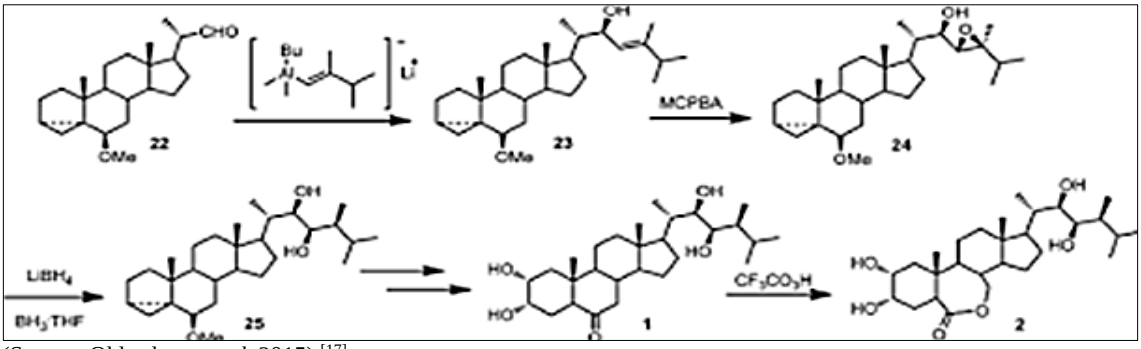
(**Source:** Ahammed *et al*. 2020) [1]

Fig 3: Brassinosteroids as Enhancers of Stress Tolerance in Vegetable Crops

In addition to this, BRs actively improve the drought, salt, and heat resistance of plants through stomatal closure, osmotic adjustment, and activation of stress-responsive metabolic pathways (Dehghanian *et al*. 2021) [4]. Besides these alterations to conserve energy and decrease water loss; they also sustain appropriate photosynthesis and absorption of minerals, which are required during drought or stress conditions.

Synthesis and Implications

The collection data of the two research questions portrays that brassinosteroid is a determinant sustainability factor in vegetable production through the enhancement of yield, improvement of quality and supplement of physiological processes of photosynthesis and nutrition circulation. The improved efficiency of BRs in these areas underlines their potential as an effective tool for the emergence of better, more resilient agriculture as weather extremes make farming even more difficult (Oklestkova *et al*. 2015) [17]. The data point out brassinosteroid use and management which could be at the same time, allowing a more accurate outline of crop strategies better resource use efficiency and a lower impact on the environment. This is crucial in today's world of farming because sustainability is an achievement.



(Source: Oklestkova *et al*. 2015) [17]

Fig 4: Synthesis of Brassinosteroids

Brassinosteroids correspond well to productivity and sustainability fields that are based on agriculture. In the future, more emphasis is needed on standardising BRs into farmers' protocols because different kinds of crops and environments need different technical solutions.

Results

The results that have been generated throughout this research prove the importance of BRs for crop productivity, photosynthesis efficiency, and nutrient acquisition. The findings will be subsequently depicted according to the two main headings, which are the research questions.

Results on Yield and Quality Enhancement

The study has shown that growing vegetables under the impact of brassinosteroids gives the highest crop yield. Those plants that are given BRs all the time will gain extra pounds; consequently, they will have extra leafage, thicker stems, and firm roots. The improved anatomical features would further promote economic activities, in the final analysis. Here, veggies like tomatoes and cucumbers are likely to be bigger and heavier after soaking in similar BR solutions (Fuentes *et al*. 2019) [6]. In the aspect of quality, brassinosteroids have been clearly shown to improve many features that are dear to consumers and marketers. Vegetables treated with BR have a significant increase in colour intensity, resembling products such as green leafy vegetables like spinach and lettuce. Not only does the frost lead to the better quality of these crops, but consumers also prefer crisp vegetables and fresh items. Furthermore, these plants not only have a higher market value but also boast a greater concentration of vitamins and minerals than conventional crops, meaning they are not only economically more attractive but also more nutritionally valuable.

Results on Photosynthetic Efficiency and Nutrient Uptake

Brassinosteroids, moreover, play an active role in regulating the flowering of vegetable plants. It is demonstrated that photosynthesis is enhanced by optimising chloroplasts, aside from heightening the level of chlorophyll content in leaves (Hu *et al*., 2022) [9]. As a result of this, there is more intense light absorption and conversion into yield energy, and thus plants can grow more even under normal and stressful conditions. BRs also work in another aspect that increases the uptake of nutrients by plants. The growth and activity of the roots increased, leading to more soil area exploration and enhancing the uptake of nutrients. These nutrients are of great significance to a plant's health, and they thus enhance the capacity of the plants to take up nitrogen, phosphorus, and potassium, which are important for their growth. Alongside enabling plants to grow, the greater ability of plants to uptake nutrients also increases plants' resilience, namely low soil fertility.

Synthesis of Findings

Results and syntheses from both sections, however, show that the function of brassinosteroids is not simply to raise the primary growth factors of leaf vegetables but also to make them tolerant to environmental stresses. The steady increase in yield and quality in a good crop variety signifies that BRs can be widely used to bring about higher productivity in agricultural methods (Kothari & Lachowiec, 2021) [12]. Furthermore, photosynthetic efficiency and goodness in nutrition are the entire benefits of BR breeding that almost sustain the crop production system. BRs cannot close these gaps, but plants can learn how to efficiently use resources, and they will keep yield levels high and grow in diverse situations, like resource limitations and climate change.

The work outcomes clearly show the prospect of brassinosteroid promoters both increasing yield and complying with environmental requirements in tomato production. The ability to unquestionably enhance yield level, quality, photosynthetic efficiency, and nutrients has made them the most effective solution not only to food security challenges but also to protect the environment.

Table 1: Effects of Brassinosteroids on Growth, Yield, and Abiotic Stress Mitigation in Vegetable Crops

Parameter	Effect of Brassinosteroids
Growth	Promotes cell elongation, division, and differentiation enhancing overall plant growth. (Lin, 2020; Figueroa-Macías *et al*., 2021) [15, 5]
	Activates genes and biochemical pathways leading to protein synthesis necessary for structural and functional roles in plants (Lin, 2020) [15].
Yield	Increases the size and weight of fruits and vegetables like tomatoes and cucumbers through enhanced cellular expansion and changes in cell wall properties (Li *et al*., 2023) [14].
	Contributes to larger and more abundant harvests by speeding up photosynthesis, which facilitates more effective water and nutrient uptake (Figueroa-Macías *et al*., 2021) [5].
Abiotic Stress Mitigation	Enhances resistance to extreme temperatures, soil salinity, and dryness by regulating stress-responsive metabolic pathways and osmotic adjustment (Swain *et al*., 2023) [25].
	Improves drought, salt, and heat resistance through mechanisms like stomatal closure and activation of antioxidant enzymes (Ahammed *et al*., 2020; Dehghanian *et al*., 2021) [1, 4].

This table provides a concise overview of how brassinosteroids impact various critical aspects of vegetable crop production, focusing on their role in promoting growth, enhancing yield, and mitigating abiotic stresses. Each point is supported by references from the literature to ensure the credibility and traceability of the information.

Conclusion and Recommendation

Conclusion

The trial proved that the brassinosteroids led to a markedly higher yield of vegetables, more photosynthesis efficiency, and improved nutritional uptake. This implies that brassinosteroids will develop the challenge of balancing and pushing up agricultural productivity and sustainability. Brassinosteroids enhance growth, stress tolerance and resource economy, thus plants adapt to variable conditions for enhanced growth under different environments in the future. This brassinosteroid response, therefore, gives an honest upshot in terms of the production of high-yielding, superior crops which could contribute to the resolving of food insecurity either at a local or global scale.

Recommendation

To make the most of brassinosteroids in farming, the following suggestions are made based on the results:

1. **Use of BRs for Crop Management:** Integration of brassinosteroids into fertilisation for latter times may optimize harvesting yield and grade.
2. **Tailor BR Application:** The dosage guidelines applicable to each crop type and climate should be worked out to ensure efficacy and safety.
3. **Expand Research:** The employment of specific BRs on a wider range of vegetable crops is recommended for further study, especially under various climatic conditions.
4. **Promote Sustainable Practices:** Make BRs available as a new instrument of sustainable agriculture to increase resource utilisation and environmental sustainability.
5. **Educate Stakeholders:** Educate farmers to use brassinosteroids wisely to achieve maximum efficiency.

Future Perspective and Drawbacks

It can be said that the role of brassinosteroids (BRs) will become more vital in agriculture due to their beneficial effects on crop tolerance and productivity, as well as the high range of problems that are caused by climate change (Zhang *et al*., 2023) [29]. Nevertheless, this should be an integrated process, disparaging with the manufacturing of customised application protocols for crop types and the environment. The guarantee of this is that the drug is both effective and safe. These findings are optimistic, however, research into BRs and other phytohormones' actions and effects on the environment is still needed in the future. On the other hand, it is not enough to focus on whether biodiversity has been genuinely protected and to help produce viable economic alternatives for wastewater recycling in the future of agriculture.

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